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The Sustainment of a Spheromak by DC Helicity Injection

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1. Introduction

A spheromak fusion reactor would be simple and inexpensive, and might actually work. The absence of both toroidal field coil windings and central-column stack reduces complexity and means that the toroidal plasma will be simply connected and compact. Intrinsic self-organisation, driven by DC edge currents, provides the means by which toroidal current becomes driven. The benefits of this engineering simplicity would be realised in the ultimate cost of a reactor. Previous spheromak experiments have produced good confinement with a simple design. 1MA toroidal currents, hard X-rays and β-limited discharges were all observed in CTX and subsequent theoretical studies pointed to the presence of good core-confinement during the decay phase[1][2].

2. The Sustained Spheromak Physics Experiment, SSPX

SSPX [3] was commissioned in 1999 by the DoE as a 'Concept Exploration' device to assess the confinement properties of the spheromak: specifically whether the self-organising properties occurring during the sustainment of the spheromak will allow for good confinement. SSPX is a 1m diameter, Marshall-gun driven spheromak, similar in design to CTX, SPHEX, and FACT, although differing substantially by virtue of a flexible initial flux-geometry, provided by 9 vertical field coils (figure 1). These coils, once installed, will allow a variety of spheromak formation and sustainment configurations to be investigated. Two separate banks form (10kV, 10mF, 0.5MJ) and sustain (5kV, 120mF, 1.5MJ) the spheromak – a typical time-history of a SSPX sustained shot is shown in figure 2.

SSPX has a comprehensive diagnostic set [4]. Profile Thomson scattering, CO2 interferometry, ultra-short pulse reflectometry, Hα array, 16-chord bolometry and the Transient Internal (magnetic) Probe will provide profile information. Magnetic field coils mounted around the plasma edge provide information for mode analysis and equilibrium reconstruction. VUV and visible spectrometers and monochrometers provide important data for impurity control. TV cameras provide views of the injector and midplane.

3. Surface conditioning

A rigorous campaign of glow-discharge cleaning, and shot conditioning lead to the reduction of impurity partial pressures to give base pressures ~2.5×10^{-8}Torr[5]. Tungsten plasma-facing surfaces mitigate sputtering and Ti gettering of the vessel and plasma-facing components further reduced the impurity concentration, allowing for the burn-through of most major impurities during the spheromak discharge. When the ratio of J/n was increased greater than 1e-14Am, radiation was no longer the dominant loss channel and clear MHD activity was observed[6].

4. Formation experiments

Operations with only the formation bank (FB) allowed the study of theoretical formation thresholds, surface conditioning, initial mode analysis, and the development of diagnostics and models. It was found that the spheromak formed in agreement with theoretically predicted thresholds – changing the initial flux configuration allowed the threshold to be lowered, facilitating sustainment at lower injected currents ('partial flux core'). CORSICA fitting revealed that the total toroidal current reached ~500kA, but that the total stored magnetic energy was only a small fraction of the total input energy (low 'efficiency' <15%). Helicity considerations showed that this efficiency could be increased by changing the initial flux configuration – more closely matching the eigenvalue of the injector to that of the spheromak. Stored energy increases of ~50% occurred.

5. Sustainment experiments

Sustainment of 400kA spheromaks for ~2ms have been demonstrated with around 1/2 maximum bank charge. The FB initiates the discharge, driving toroidal current up to ~400kA. The sustainment bank (SB) is then discharged and the plasma is sustained. The density is typically ~1e14cm^{-3} – initially the plasma radiates strongly, until J/n exceeds 1e-14Am. During sustainment, the n=1 mode is present and during decay, the n=2 arises due to current-profile changes (from CORSICA, see below). Previous predictions of toroidal current build-up (to 1MA) have yet to be realised, in part due to work required to re-enforce the bank circuit. The impedance of the injector has been determined to be similar to that of CTX ~1-10mOhms – this data is used as input to numerical models (see below). Most sustainment experiments have been performed with the partial flux-core initial flux configuration for reasons mentioned above.

Initial experiments with the SB characterised the discharge. It is found that the density of the SB discharge increases with FB charge, also that operating close to threshold in the standard flux configuration lowers density (~5e13cm^{-3}). The field of the FB discharge can be increased by the SB pulse. For weakly sustained spheromaks, the decay period is extended considerably and the onset of the n=2 mode can be delayed. By delaying the firing of the SB, thus allowing ohmic heating of the plasma to occur, OVI/OV ratios can be increased throughout the period of the discharge and decay times can be increased. Scanning through a range of puff-plenum pressures revealed that density could not be affected, mainly due to an inability to breakdown at lower plenum pressures – new 'fast' puff valves have been installed that will allow for breakdown at a wide range of plenum pressures.

6. Fluctuation analysis

After surface conditioning (He shot conditioning and Ti gettering), the discharges exhibited long decay times (~1ms) and clear MHD activity (see figure 3): n=0 occurred during the initial formation and was associated with an instability in the injector that lead to the injection of helicity in discrete bursts; the n=1 'dough-hook' mode observed in all gun-driven spheromaks occurred subsequently; and during the decay, an n=2 toroidal kink mode established – observed in CTX in clean warm (~50-100eV) plasmas. The plasma is rapidly terminated with the onset of a tilting instability (mostly observed in partial flux core config.).

7. Modelling

0,1,2 and 3D models of SSPX are being developed/refined. 0D: the spheromak is modelled as a circuit element represented by an inductive and resistive impedance – SPICE models have been refined by including a large inductive component. The circuit model is used as an input to the 1-D heat and energy transport code [7] employed to predict the evolution of field and core temperature. Good agreement was found with formation experiments – the code is now used to determine the evolution of the sustained plasma. Figure 4 shows a build-up to ~1MA toroidal plasma current with a core temperature reaching ~200eV for a sustainment case in which the gun voltage remains clamped at 700V. CORSICA – a 2-D ideal MHD code - is employed to determine the equilibrium fields by varying the total toroidal current and internal current profile to fit to poloidal field measurements made at the plasma boundary (example is shown in figure 1)[8]. CORSICA can now determine the evolution of internal parameters by time-slice fitting. An example is shown in figure 5 – for this sustainment pulse, toroidal currents of ~400kA were observed, and the safety-factor profile was seen to span 0.5 during the decay – commensurate with the observation of the n=2 mode. A full 3-D nonlinear resistive time-dependent MHD code (NIMROD [9][10]) is now being employed to simulate the spheromak plasma in SSPX-similar geometry. Preliminary results model formation and reproduce asymmetric features observed in the driven phase of the spheromak – notably the n=1 'dough-hook': a high current column radially displaced from the geometric axis (figure 6).

8. Future experiments

In the near future, SSPX will be modified with a set of vertical field coils that will allow a range of formation schemes to be investigated. Of principal concern is the 'efficiency' of coupling injected power to spheromak field energy – initial experiments in bias-coil-like configurations pointed to increased efficiency.

9. Summary

SSPX is operating routinely with a nearly complete diagnostic set. Plasmas are not radiation dominated and exhibit MHD activity. Initial experiments with the sustainment bank – supported by strong modelling efforts - show the possibility of building to higher fields.

Acknowledgments

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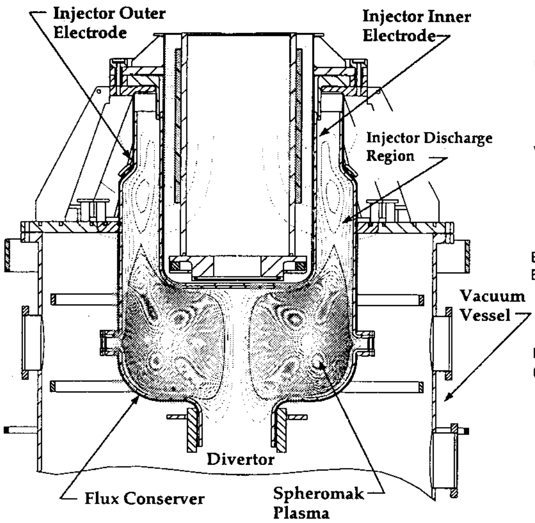

Figure 1. SSPX with CORSICA equilibrium reconstruction.

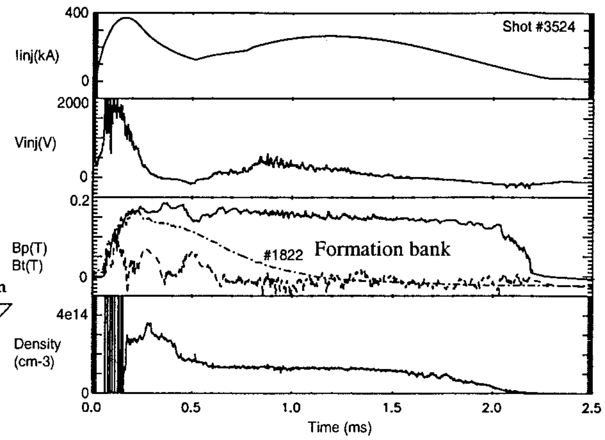

Figure 2. Typical sustainment time-history of injected current, voltage, edge field and line-averaged density.

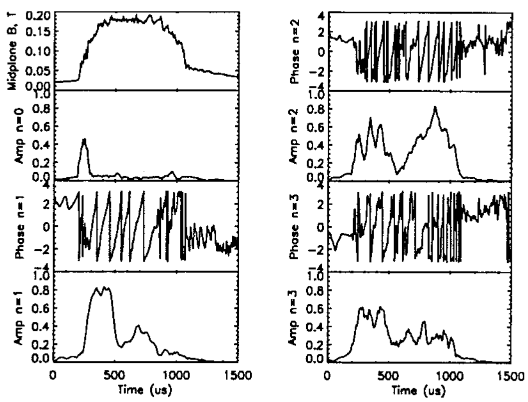

Figure 3. Discrete Fourier analysis shows evolution of n=0,1,2 and 3 modes in a formation shot.

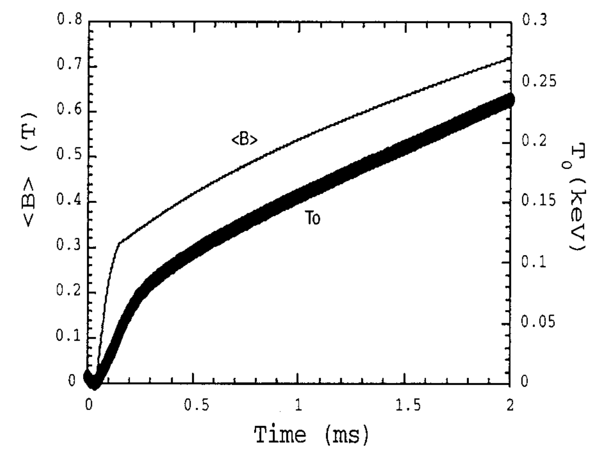

Figure 4. 1D energy and heat transport code predicts build-up to ~1MA and core electron temperatures of ~200eV.

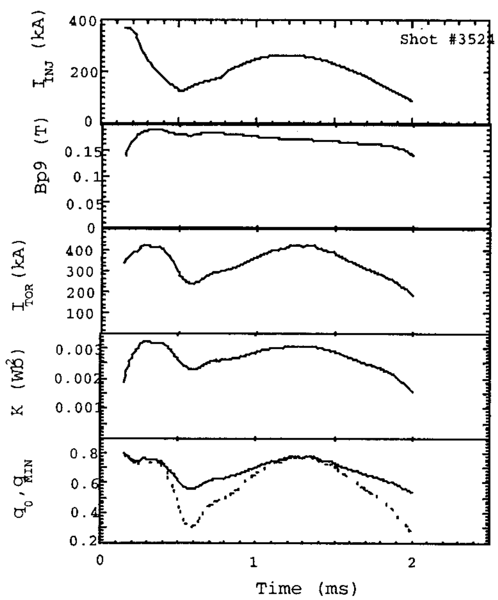

Figure 5. CORSICA time-slice fitting shows evolution of internal parameters and profiles.

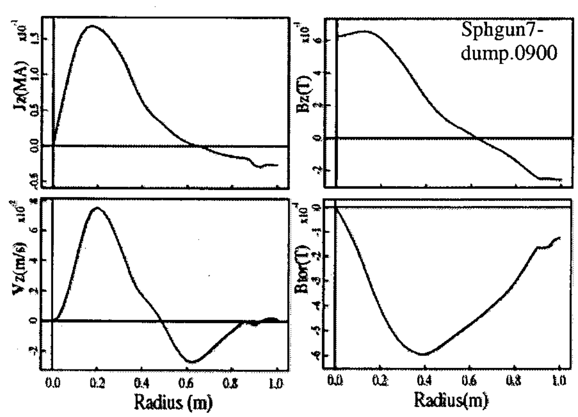

Figure 6. NIMROD simulations of the driven phase show strong asymmetries – notably a column of high current displaced from the geometric axis. Profiles are produced along an equatorial radius.